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SENSATION PERIOD, A CONTRIBUTION TO THE THEORY OF TIME, SPACE, AND MOTION SENSATION

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ABSTRACT. A historical review of the development of sensation time is followed by discussions of the correlation between sensation time and reaction time, based on psychological tests patterned on astronomic observations of star transits in various types of telescopes. Personal equation, systematic errors in reaction times, and response to various sensory stimuli are explained and discussed. Tabulated and composite results indicate that the reaction time depends on the intensity of the sensory stimulus and that reaction times to sound stimuli and electric skin stimuli are shorter than to light stimuli. Differing results of various authors are explained on the basis of personal equation, anticipatory reactions, and physical condition of the individual. A theory is developed for proving that stimuli of equal sensation time necessarily mean equally long reaction times.

PART II

HISTORICAL DEVELOPMENT OF THE QUESTION OF SENSATION PERIODS

1. Astronomic Time Determination

In 1796, the Director of the Greenwich Observatory, Maskelyne, during astronomical observations at the Royal Observatory (Part III, p.339, 1796), reported that his assistant Dr.Kinnebrook had gradually taken the habit of observing the transits of stars through the reticle of the meridian circle about 0.5 - 0.8″ later than Maskelyne himself. Maskelyne stated that Kinnebrook, in 1794 and at the beginning of 1795, observed the transits in conformity with himself but that, starting in August of the same year, he recorded the transits half a second later; this difference increased in the year 1796 up to 0.8″ so that it seemed improbable that his assistant would ever return to a correct observation method. For this reason, Maskelyne was forced to discharge his assistant. Following this report, Maskelyne described a method introduced by Bradley according to which the positions of the stars were recorded during the individual pendulum deflections of the astronomic clock, before and after passage across the middle wire of the reticle, thus permitting measurement of tenths of a second. According to instructions by Bradley, the observer, so as to detect the instant of star trans-

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* Numbers in the margin indicate pagination in the foreign text.

it, had to center his attention first on the star and then again on the reticle of the meridian circle, i.e., to distribute his attention over both. Maskelyne was of the opinion that his assistant did not strictly follow this stipulated method but used his own arbitrary procedure.

The famous Königsberg astronomer Bessel who came across this particular report made the following statement: "Considering that the stars as well as the cross wires are fully discernible in average-quality meridian circles and that the motion during one second, even at a magnification of only 60 - 80 ×, is already so great that the observer ordinarily is sure of his measurement to within one tenth of a second, the discrepancy between Maskelyne and his assistant seems almost incredible. Considering furthermore that Kinnebrook must have had the desire to observe the transits as early as possible so as to approach the real conditions as closely as possible, there can be no doubt that an unintentional constant difference may have existed between the two observers, which by far exceeded the limits of random uncertainty and not only would require a detailed investigation with respect to astronomic observations but also appears quite peculiar from the anthropological viewpoint." These considerations by Bessel led to the discovery of the so-called "personal equation" (Ref.1). In 1819, Bessel made experiments in collaboration with Lindemann and Encke using a meridian circle, in which each of the astronomers observed a few star transits. However, these attempts yielded no useful result; the observations were too few in number and the differences too small. It was only during the winter of the following year that Bessel, by comparisons with Walbeck, obtained significant differences: /5

$$\text{Bessel} - \text{Walbeck} = +1.041$$

Based on this expression, the term "personal equation" was coined. Bessel observed the transit about 1″ later than Walbeck:

	Bessel — Argelander	= — 1.223″
	Struve — Walbeck	= — 0.202″
October 1814	Bessel — Struve	= — 0.044″ (Ref. 2, 3)
November 1820	" "	= — 0.680″
January 1821	" "	= — 0.799″
June 1823	" "	= — 1.021″.

One could speak here of an increasing difference in the measurements, as it apparently became evident in Kinnebrook's case. Similar results would be obtained also from the measurements by Main and Rogerson which extended over 14 yrs and led from coinciding values to a difference of 0.70″. One could think here of an increase in the personal equation with progressing age of the observers, if it were not for the fact that Peters had reported differences that occurred during one and the same day between the observers Wolfers and Nehus (Ref.4).

Differences between Main and Rogerson

1840	— 0.15″	1848	+ 0.37″
1841	— 0.08″	1849	+ 0.39″
1843	+ 0.20″	1850	+ 0.45″
1844	+ 0.18″	1851	+ 0.47″
1845	+ 0.20″	1852	+ 0.63″
1846	+ 0.26″	1853	+ 0.70″
1847	+ 0.35″.		

Changes in the observation conditions also caused changes in the personal equation. When measuring occultation of a given star at the dark lunar limb, the following was found:

Bessel — Argelander = − 0.222″

i.e., much smaller differences. If a second clock and a half-second clock were used in the measurements, it was found that

Bessel (second clock) — Bessel (Halbsekundenuhr) = — 0.494″ 16
Bessel „ — Argelander „ = — 1.227″.
(half-second clock)

The fact that the personal equations varied even under different observation conditions left no doubt on the reality of this phenomenon. Bessel himself wrote: "The different experiences show that no observer, even if he is convinced of strictly following Bradley's observation method, can ever be certain that he is giving absolute instants of time with complete accuracy. It would be highly desirable to find a means of making exhaustive investigations of this enigmatic phenomenon; however, I believe this impossible since the operations responsible for the difference proceed subconsciously. Nevertheless, astronomers must attempt to recognize errors in the results due to this source and to avoid them as far as possible. The influence on the meridian differences of the localities is obvious. For example, if Dr. Argelander would have determined the time for his star occultations, then the town of Königsberg according to his observations would be by one second of time farther East than according to my own observations." This would constitute a difference of about 350 m!

It is true that the assistant Kinnebrook had never become outstanding as an astronomer, but his discrepancy with Maskelyne did lead to the discovery of the personal equation. Since this discovery formed the start for a large number of astronomical, physiological, and psychological investigations which, on the one hand, were to eliminate the personal difference in astronomical time determinations and, on the other hand, to measure the sensation time, the name of Kinnebrook will be permanently connected with the history of astronomy, physiology, and psychology and this even more so as it will be demonstrated that it is exactly the classical observation method by Bradley which is least suitable for obtaining concordant results.

Until then, astronomers made time determinations with the so-called visuo-auditory method. In this method, the pendulum deflection of a clock is used for determining the instant at which the comparison star passes across the middle wire of the meridian circle (transit circle, transit determination). The time is estimated in tenths of a second. Because of the shortness of one second, it is doubtful whether it is actually possible to estimate 1/10 sec. However, here it is not a question - as frequently assumed - of a time estimate but rather of a space estimate. As soon as the star enters the field of view of the telescope, the observer checks the time on the clock and, during the observation, counts the second beats. It happens rarely that the star crosses the middle wire exactly at the instant of a second strike, usually being still a certain distance away from the wire at the first second strike and already a certain distance on the other side of the wire at the next second strike. For example, if the segment ahead of the middle wire is 1/4 of the distance to be covered by the star between the two second strikes, the instant of transit will have been determined with an accuracy of 0.25″.

In 1842, Arago (Ref.5) thought to eliminate the personal error by defining /7 the instant of transit by stopping a clock whose hand indicated the time. Arresting of the clockwork was done by releasing a trigger held in the hand of the observer while looking through the telescope. This mode of observation became known as recording method and was quite similar to the reaction time methods used later by physiologists and psychologists. In 1851, Bond published a paper in the Reports of the British Association (Ref.6) on experiments with electric recording, in which apparatus similar to electric telegraphs were used. Key recording and paper strip charts, moved by a clockwork known as chronographs, were used.

Prasmowski and Hartmann (Ref.7, 8) mentioned that training is of great importance in transit determinations and that such training should be obtained on specially designed apparatus, simulating the transit processes by means of artificial stars. Instruments of this type were used by Hartmann and Hirsch (Ref.9). A.Hirsch, the Director of the Neuchâtel Observatory, used a Hipp chronoscope constructed on his request, for making transit determinations according to the recording method, using artificial as well as real stars; for comparison, he also made recording experiments with other sense organs. The experimental setup was as follows: On passage of the artificial star across the middle wire of the telescope, the pointer of the chronoscope was automatically started in motion by electric means; the chronoscope was arrested, by pressing an electric key, at the instant at which the observer saw the transit of the star across the wire. In this manner, it became possible to read the time with an accuracy to 1/1000″. When using artificial stars, extremely short values were initially measured. Hirsch attributed this phenomenon to excessive velocities of the artificial stars. As soon as lower velocities were used, corresponding approximately to the velocity of an equatorial star, greater personal errors were measured which were of the same order of magnitude as in observations of natural star transits. In further experiments, in which also Plantamour and Wolk (Ref.10, 11) partici- /8 pated, greater fluctuations occurred which, for the case of Hirsch, amounted to 0.013 - 0.362″. In some cases, these values even became negative, since the observer reacted before the star had passed across the middle wire. This behavior was attributed to an anticipation of the passage, as it readily may happen when observing a star that gradually approaches the transit point. C.Wolf (Ref.12), using a high-accuracy instrument designed on the principle of the visuo-auditory method, obtained a constant error of 0.1″ at uniform mode of observation; this error remained at the same magnitude even when replacing the light stimulus by a sound stimulus or by an electric stimulus applied to the skin. Similar experiments were made by the astronomers Harkness, Eastmann, H.G.van de Sande Backhuyzen, and Küstner (Ref.13 - 16). All these investigations clearly demonstrated the personal difference of the observers as well as the gradual changes in the reaction of the individual observers, as discussed above. A larger series of studies showed an increase in the personal equation for stars of lower magnitude, i.e., lower brightness. This involved the so-called brightness equation developed by the astronomers Argelander, van de Sande Backhuyzen, Turner, and Schäberle (Ref.17 - 19).

Detailed investigations by these astronomers definitely prove that the personal equation exists and also demonstrate its dependence on the apparent magnitude of the stars (brightness equation), on the declination of the star (velocity equation), and on the skill of the observer. Thus, it seems logical that attempts were made to develop methods for eliminating the personal error. Such a possibility was apparently given by the so-called physical recording micrometer developed by Repsold (Ref.20). In the Repsold micrometer, a reticle is moved /9 through the field of view of the meridian circle either by hand or by a clockwork, at a speed corresponding to the stellar velocity, with the observer having the task of making the wire coincide with the star. In this case, the transit of the star and of the middle wire through the local meridian is recorded automatically. Originally, it was believed that this method might eliminate the personal equation; however, it was soon found that the personal equation still appeared in this method and that an influence of the velocity and brightness of the stars existed [Zeipel, Nörlund, Wirth (Ref.21 - 23)]. It must be considered that in the case in which the star, for example, leads the moving wire at a certain point, a certain time will elapse before this lead is perceived (sensation of change) and that, beyond this, some more time will elapse before the observer - as a function of his personal equation - will make the wire and star coincide again. In fact, a critical investigation by Wirth showed that considerable fluctuations occurred in individual observations, going as high as 3 sec; however, by introduction of a number of contacts into the micrometer, these errors are compensated and reduced to an order of magnitude which, under favorable observation conditions, is close to 30 σ. Accordingly, the Repsold micrometer is not a truly physical instrument but does produce a considerable increase in measuring accuracy which previously could be attained with conventional recording methods only by skilled observers. This made it logical to record star transits by photographic means, so as to eliminate the personal equation. However, this idea could not be realized, since the sensitivity of photographic plates is insufficient for such stellar photographing. The sensitivity of the eye is far greater than the sensitivity of photographic plates. In 1927, the Swedish astronomer Bengt Strömgren (Ref.24) described a method that permitted an automatic transit determination and thus completely avoided the personal equation. On passage through the meridian circle, the image of the star falls on a photosensitive selenium cell; the resultant minimal photoelectric current is amplified in amplifier tubes and the instant of entrance of the current is defined by means of sensitive galvanometers.

At this point, we should mention an important observation by the Norwegian /10 astronomer O.Pihl (Ref.25), made in time determinations with the occultation method and offering the possibility of measuring the absolute magnitude of the personal error. The occultation method essentially consists in having the star pass through a segment, left free in front of the aperture of a diaphragm in the field of view of the telescope, and then having the observer indicate the instant of time at which the center of the path is passed. Pihl noted that the star did not appear at the periphery of the diaphragm but more or less jumped a certain distance into the path and then left the diaphragm at the other edge. O.Pihl correlated this delayed appearance of the star with the sensation time and made an attempt to calculate this time from the displacement of stars of different magnitude; he obtained values between 0 and 638 σ. However, these values are subject to certain doubts; this was responsible for the fact that Pihl's observations were generally disregarded. It seems logical to reject the zero values of the personal error since it can hardly be assumed that, even in the presence of strong light stimuli, the time needed for the development of sensation would ever approach zero; on the other hand, the large values closely resemble the considerable personal differences which had been recognized earlier, so that special attention should be paid to this particular point. The finding reported by Pihl should be encountered not only in the occultation method but also in any method in which it is a question of determining the instant of time at which a given star emerges from behind the lunar limb.

2. Complication Experiments

Originally, only astronomers were interested in the personal equation and made attempts to subject the pertaining physiological and psychological problems to experimental analyses; gradually, however, also physiologists and psychologists became interested in these problems. Here, we should specifically mention the investigations made by Helmholtz, Donders, Exner, and Wundt who frequently took over or simulated methods familiar to astronomers. This greatly enriched the physiological methodics and, in addition, popularized the accurate working methods of astronomers as well as the manner in which the efficiency of their methods were tested. Astronomic methodics also furnished the Hipp chronoscope frequently used in psychology, as well as Wundt's method which corresponds, in its general aspects, to the visuo-auditory method and which, in agreement with Herbart, was later designated as "complication method". Aragos' recording method formed the basis for methods used in determining the personal equation of various sense organs, in defining the velocity of propagation of excitation in sensory nerves by Helmholtz, Baxt, Schelske, F.Kohlrausch, Hankel, Donders, /11
de Jaager, and v. Wittich (Ref.26 - 32), and designated by Exner as method of reaction time measurement.

Wundt's complication method (Ref.33) had the purpose of comparing the actual ratio of two sensory stimuli with the resultant sensations. The apparatus used in these methods, depending on their particular design, became known as complication clocks or complication pendulums. The complication clock basically is a clock whose hands are able to move at differing speeds and are provided with a device by which, at the instant of passage of the hand over a certain graduation of the dial, a gong or strike is released. The point of such release can be varied at will. In complication experiments, it always happens that the graduation of the dial at which the sound impression is perceived does not correspond to the locus of its real occurrence but coincides either with an earlier or a later point. In reality, only positive time displacements should have been expected, which would indicate the time elapsed between the physical effect of the gong and its perception, meaning that information should have been obtained on the sensation time of the human ear. An attempt had already been made by Bessel to interpret the positive and/or negative time shifts, by assuming that - in the former case - the subject would first see and then hear while - in the latter case - he would first hear and then see. However, Wundt objected to this formulation and stated that it was based on the erroneous assumption that seeing and hearing constitute undivisible more or less mutually bypassing processes and that, at a given instant, only one impression could be perceived by the attention. He maintained that this is by no means the case, as demonstrated by the familiar simultaneous perception of light and sound impressions. He believed that the connection between both disparate sensory impressions would be simultaneous in either positive or negative time shifts but that a time illusion existed at simultaneously present concepts, produced by changes in intensity and direction of attention to one of the stimuli. Thus, any distinct mark, made /12 on the graduations of the scale, will cause a mental association of the sound stimulus with this particular point. O.Klemm (Ref.34) used a complication clock without face, having a dial on which the observer could displace a small mark and adjust it to the point at which position of the hand and strike of the gong coincided. Positive and negative time shifts occurred also under these conditions, but distinct influences of the direction of the pointer motion, the training of the subject, and the trend of attention could be demonstrated. Similar observations were made by v. Tschisch (Ref.35) who worked with pressure stimuli and electric skin stimuli as well as by C.Wolf (Ref.36) who replaced the bell signal by an optical signal, so that two optical stimuli were presented. Complication experiments were also carried out by Pflaum, Angel and Pierce, Geiger, Heyde, Michotte, and Moede (Ref.37 - 42).

In addition, we should mention experiments reported by Helmholtz (Ref.43) more than 50 years ago in papers presented at the Berlin Academy; these were experiments to measure the time required for a visual impression to reach the level of awareness. This method was later used by S.Exner (Ref.44) in measuring the differences of sensation times for light stimuli of differing intensity. The method was based on the following trend of ideas: If, in observing with fixed regard a certain point in the field of view, a weak light stimulus is followed by a strong light stimulus separated by a short interval, the weak stimulus will be extinguished despite the fact that it precedes the strong stimulus in time. If the interval between the two stimuli is lengthened, a time interval will result at which even the weak prior stimulus is perceived. Helmholtz and Exner were of the opinion that the two stimuli can be sensed separately only if the intervening interval is greater than the difference in the sensation times of both stimuli. In this manner, Exner was able to define sensation time differences /13 ranging between 0.075 to 0.187 sec and to demonstrate that a logarithmic relation exists between intensity of stimulus and sensation time. Basically the same method was used by Baxt (Ref.45), except that he replaced the simple light stimulus by letters and figures which he then extinguished by a subsequent extinction stimulus. One would be justified to apply here the term perception time rather than sensation time, to express that the time measured by Baxt included already higher consciousness phenomena. The Helmholtz-Exner method, despite the fact that it is entirely plausible, never penetrated into the general literature. The obtainable results were too vague and it was too readily possible that the resultant data were falsified by the intervention of a coalescence of both stimuli or by mutual interference of the stimuli. In recent times, experiments with the extinction method by Piéron (Ref.46) were resumed, and M.Monjé (Ref.47), on our suggestion, subjected this method to a critical and comparative investigation.

3. Determination of Simultaneity of Disparate Sensory Stimuli

Specific experiments on the simultaneity of two disparate sensory stimuli were first made by Exner (Ref.48), for determining the minimum still perceptible time difference between disparate sensory stimuli. Exner compared the flash of an electric spark with the tone of a smartly rapped glass and found that the light stimulus must have a lead of $24\ \sigma$ to be perceived simultaneously with the sound stimulus. Investigations on the same problem, made by Bloch, Weyer, Peters, Minnemann, and Geigel (Ref.49 - 53) showed that the sensation of simultaneity respectively nonsimultaneity depends on a number of factors, namely on the type of attention level, training or skill of the test subject, and in- /14 tensity and duration of the presented stimuli, i.e., on conditions quite similar to those observed in complication experiments. Training and attention promote differentiation of simultaneity and nonsimultaneity. Under otherwise equal conditions, the stimulus conditioned by attention, respectively the stronger and longer stimulus, is perceived earlier. Consequently, it is completely unjustified to generally ascribe a shorter or longer sensation time to a given sensory region.

4. Reaction Time Experiments

Reaction time was designated by Exner (Ref.54) as the time elapsed between presentation of a sensory stimulus and occurrence of a correlated voluntary reaction motion. The term "reaction time" was patterned after the term "reflex time" which is the time elapsed between stimulation of a sense organ or of a sensory nerve and occurrence of an involuntary reflex action. It is obvious that the above-mentioned sensation time, i.e., the time elapsed between stimulation of a sense organ and occurrence of the pertaining sensation, constitutes a component of the reaction time.

Investigations by L.Lange and Martius (Ref.55, 56) drew attention to the dissimilarity in reaction times relative to the sensory and motor attitude of the test subject. In the sensory attitude, attention is directed toward as rapid as possible an apperception of the sensory stimulus and thus is diverted from the motor reaction. The sensory reaction time has a greater duration, shows more extensive fluctuations, and is especially pronounced in untrained test subjects. In the motor attitude, attention is directed toward as rapid as possible an execution of the reaction. The motor reaction times are shorter and adjust themselves to a mean value after a certain training; these times show less fluctuations than the sensory reaction times. In experiments by Alechsieff (Ref.57), the following values of motor reactions were compiled, obtained with day adaptation and use of a white field illuminated by daylight:

Studies by Hirsch, Donders, Hankel, Wundt, Exner, v. Kries and Auerbach, /15 and Cattell (Ref.58 - 64), concerning reaction experiments with various sense organs, seemed to indicate that sound stimuli and electric skin stimuli will condition much shorter reaction times than light stimuli; this result also seemed to agree with the above-mentioned findings by Exner, but it must be considered here that it is rather difficult to compare two disparate sensory stimuli as to their intensity and time course. Wundt (Ref.65) demonstrated that, in the neighborhood of the threshold stimulus, the reaction times to stimulation of various sensory regions are of the same order of magnitude. The compilation given below is taken from the book on physiological psychology by Wundt (Ref.65), with similar results having been obtained also by Berger (Ref.66) and Cattell.

Threshold Stimulus	Average	Variance
Sound	337 σ	50 σ
Light	331 σ	57 σ
Tactile sensation	327 σ	32 σ

Already these data show that the reaction time depends on the intensity of the sensory stimulus. Berger measured reaction times between 338 and 200 σ, as a function of the intensity. When using threshold stimuli, the values agree with those given by Wundt. At increasing intensity, the reaction times first decrease rapidly and then more slowly, gradually becoming adjusted to a minimum of about 200 σ and thus approaching values corresponding to those given by Alechsieff. In addition, the values are within the same order of magnitude as recently reported by Vogelsang (Ref.67) as well as by Pottevin and Taillie (Ref.68), in reaction time experiments with light stimuli. The difference in the reaction times, as a function of the stimulus intensity, would thus be approximately /16
140 σ. Piéron (Ref.69) made an attempt to use the dependence of the reaction time on the stimulus intensity for gaining information on the time required for apperception of a sensory stimulus. He obtained maximal values of about 150 σ. However, an attempt to obtain data on the duration of the processes in the sense organ and in the sensorium, by varying the stimulus duration and extending the stimulus itself, apparently led to no statistically reliable result.

In the totality of the experiments, the personal equation of the observers was always prominent. Léa Feygin (Ref.70) emphasized that observers who showed a shorter reaction time to the sound stimulus also exhibited a shorter reaction time to the light stimulus, meaning that the differences in personal equation apparently extend over the various sensory regions. The influence of duration of the stimulus on the reaction time was investigated by Wells and Léonnard (Ref.71, 72); with increasing duration of the stimulus, the reaction time decreased, but Léonnard observed exactly the opposite behavior. Since, on the basis of facts gathered in the general physiology of sense organs, it must be assumed that a protracted stimulus has a greater efficacy, the results obtained by Léonnard may have to do with the fact that the time course was decelerated with increasing duration of the light stimulus. As indicated already in experiments by A.Hirsch and, more recently, also by Günther (Ref.73), a slower increase in the sensory stimulus will mean a longer reaction time. This might explain also the long reaction times when gustatory, temperature, and pain stimuli are presented.

The dependence of the reaction time on the color of the light stimulus was studied by Berger, Heumon (Ref.74) and Holmes (Ref.75). In contrast to Heumon, Berger and Holmes found that the various colors, if they are of equal brightness, will result in equally long reaction times.

A survey over the results of extensive studies on reaction times indicates that the reaction time is dependent on the following factors:

1) personal equation of the observer; /17
2) attention (sensory and motor attitude);
3) training and fatigue;
4) intensity;

5) duration and time course of the stimulus;
6) quality of stimulus.

Here, we are disregarding the numerous data having to do with the dependence of the reaction time on toxic effects such as alcohol, morphine, chloroform, tea, coffee, diseases of the nervous system, or which treat the reaction times under highly complex experimental conditions (Ref.61, p.423).

In presenting sensory stimuli of differing intensity, reaction times ranging between 180 - 200 σ on the one hand and up to 350 σ on the other hand are obtained. This order of magnitude also encompasses the values obtained in many hundreds of our own measurements, at presentation of light stimuli. However, in these limiting values it must be taken into consideration that the individual conditions on which the reaction time depends have never been systematically investigated. In this respect, caution must be exerted specifically in regard to the great personal differences, observed in astronomic time determinations. If personal differences of more than one second occur, it can be suspected that it is exactly in astronomic time determinations where conditions exist which result in long reaction times. We have been told repeatedly that the slow course of the light stimulus might be due to the low velocity with which the star moves through the field of view of the telescope. It will be demonstrated later that, on presentation of sensory stimuli of a very slow time course, much greater reaction times were measured than had been the case previously.

However, data are also in existence on much shorter reaction times. Astronomic researchers already became aware of the fact that the reaction times, under certain circumstances, may be extremely short and that even negative reaction times might occur, in which the reaction takes place before the releasing signal is given. Such anticipation is possible specifically in observing star transits since the observer sees the star gradually approach the middle wire of the reticle of the meridian circle. Attempts have been made to utilize this anticipation by anticipating the sensory stimulus to such an extent as to have the reaction take place simultaneously with presentation of the stimulus. This reduced the personal error of transit determinations, under favorable conditions, to an average of 30 σ. These anticipatory reactions had been subjected to detailed studies also from a psychological aspect.

As done by Wirth (Ref.76), the extent of anticipation can be defined by unexpectedly eliminating the sensory stimulus in a series of reactions and then determining the time at which the observer, on omission of the stimulus, is still able to inhibit the reaction. Such shortened reaction times had been obtained recently by Kühnert (Ref.77) with an apparatus constructed by Wirth; there is no doubt that these play a certain role in everyday life, especially whenever both stimulus and reaction have undergone a rhythmization or whenever, as in firing on moving targets, prediction of the target is used. It is highly probable that the personal equation plays a role also in these anticipations, but anticipatory responses furnish no data on the sensation times which are of specific interest here. Although it is of some practical importance to subdivide the reaction modes into sensory, motor, and anticipatory modes, we are mainly interested in motor reactions since they alone are able to furnish information on the duration of processes that lead to sensation, in agreement with the above-mentioned experiments by Berger, Piéron, and Vogelsang. /18

5. Indications of the Significance of Sensation Time

No matter whether the visuo-auditory method of astronomers or the complication method of psychologists is used in studying the coordination of two sense organs, or whether the question is investigated as to the extent of simultaneous perception of stimuli by two sense organs, or whether the absolute values of the personal errors are to be determined by means of reaction time experiments, it will always be the sensation time which plays a major role, i.e., the time required for apperception of the sensory stimulus. There can be no doubt that the processes leading to sensation require a certain time; first, the sensory cells must respond to the stimulus, the excitation process must be conducted over the sensory nerves to the sensorium, and the nerve cells of the various sensory centers must respond before sensation can come into being. Based on the above-discussed experiments, it must be assumed that the sensation time depends on the stimulus presented to the sense organ and on the type of excitations conducted to the sensory center. The question here is how to measure the sensation time. Where must the experiment begin? The most promising in this respect are Wundt's complication experiments, but they never led to measurement of the sensation time. Just the opposite, they yielded "negative time shifts" which could be interpreted only on the basis of hypotheses. In view of the rapidity with which sensation occurs, how could one possibly determine the instant at which the sensation is initiated, at which it reaches its maximum, and at which it just about decays? These questions are encountered by anyone working in the field of /19
sensory physiology and having occasion to observe the widely differing conditions under which the sensation time becomes manifest. In perusing the sensory-physiological literature, we encountered a large number of papers all of which emphasize the significance of sensation time. A few of these, referring to the sense of vision will be discussed here; with certain restrictions, they also apply to other sensory regions.

Exner (Ref.78) described the finding that the effect of a weak sensory stimulus can be extinguished by a stronger stimulus following the first in short succession. This would mean that the sensation of a strong light stimulus develops more rapidly and earlier than that of a weak stimulus, thus obscuring the effect of the latter. Similar findings were obtained by Helmholtz, Baxt, Tigerstedt and Bergqvist, Cattell, Becher, Stigler, Piéron, Baade, Ebbecke, and Monjé (Ref.79 - 88). Stigler, in his investigations on metacontrast, was able to demonstrate that a weak prior stimulus can be extinguished also by a stronger subsequent stimulus which is exerted on a neighboring point.

The existence of sensation time was demonstrated also in studies made by Wheatstone, Szili, v. Kries, Schapringer, McDougall, and Ives (Ref.89 - 94), /20
who made their experiments with the simultaneous use of red and blue moving light stimuli. When using two vertically arranged light slits, of which one is illuminated by blue light and the other by red light and which are moved in front of the eye fixed on a stationary point, the slits are vertically aligned when observing with the light-adapted eye while the red slit seems to lead when observing with the dark-adapted eye at reduced illumination. This would indicate a longer sensation time for short-wave light, i.e., a more sluggish reaction of the twilight apparatus which is excited specifically by the short-wave light. As mentioned especially by v. Kries, the phenomenon of "auricular fibrillation" is based on the same principle. If, as done by Szili and Schapringer,

small red and blue pieces of paper - they need not have the shape of a heart - are pasted on a dark background and if the cardboard is moved back and forth in front of the fixed eye, at reduced illumination, mutual displacements of the pieces of paper will occur, resembling a type of flutter in that the red pieces seem to lead in the direction of motion. The same principle is involved in the phenomenon described by Hess (Ref.95), in which, of two vertically arranged and differently illuminated light slits, moving in front of the fixed eye, the brighter slit seems to lead. In addition, we should mention observations by Mach, Dvořak, and Bethe (Ref.96 - 98), demonstrating the difference in sensation time of different retina points. However, the differences were attributed to a differing attention set. At instantaneous illumination with a long Geissler tube, the light sensation seems to originate from the point to which attention had been directed. Fuchs (Ref.99) connected this phenomenon, on which increased emphasis has been placed in recent times, with the sensation time of different /21 retina sites.

The problem of sensation time entered a new stage at the time, in 1922, when four different authors independently discovered or developed methods that permit measuring the sensation time in the region of the sense of vision. These are the methods developed by Fröhlich and Hazelhoff, with which the absolute values of sensation time can be measured, as well as the methods developed by Pulfrich and Helmholtz, Exner, and Piéron, with which the differences in the sensation times of both eyes or one eye can be determined at different strength of illumination. Later Sections of this paper will treat the results of these methods.

PART X

RELATION BETWEEN SENSATION TIME AND REACTION TIME

The methods for measuring the sensation time furnish information on the extent of the subprocesses lying at the base of the reaction time. An anatomico-physiological consideration shows that the instant of occurrence of a reaction in response to a sensory stimulus is conditioned by the latency periods of a number of physiological processes whose total time constitutes the reaction time. The totality of processes, forming the basis of a reaction, can be readily subdivided into two essential subprocesses: processes leading to sensation and limited in time by the arrival of the excitation at the sensory centers of the cerebral cortex, and the motor component of the reaction which comprises the transmission of excitation to the motor centers of the cerebral cortex as well as the consequent excitation of spinal cord and muscles. Considerable information on the magnitude of the components of the reaction time can be obtained by allowing for the various reaction types determined by extensive studies on reaction times. The reaction times show considerable difference depending on the attitude of the test subject, respectively on the task to be performed. In the sensory reaction, the test subject must place special emphasis on rapid apperception of the sensory stimulus; in addition, this type of reaction time is longer than the motor reaction time, in which the trend is toward rapid execution of the reaction. Anticipatory responses in which, as mentioned above, the sensory stimulus is so to say anticipated will furnish no data on the duration of the subprocesses. The long reaction times, measured in the so-called choice reactions, are conditioned by the intercalated higher consciousness processes, whose more accurate time definition will become possible provided the values of the sensation time and of the motor component of the reaction time can be used as basis for the calculation.

Earlier, Hazelhoff (Ref.100) interested himself already in the question as to the relations existing between sensation time (S.T.) and reaction time (R.T.). The short table below gives a review over his results. This covers mean values from a large number of determinations made under equal conditions with 40 test subjects. It could be concluded from this result that, at a lower intensity of the light stimulus, both sensation time and motor component of the reaction time would be greater.

Light Stimulus	S.T., in σ	R.T., in σ	Difference, in σ
Strong . . .	94	211	117
Weak . . .	148	274	126
Very weak	201	351	150

Vogelsang (Ref.101), in analogous experiments, obtained slightly different results but his conditions deviated somewhat. It is a well known fact, repeatedly described and observed in reaction time experiments, that the sensory reaction times are less prominent after protracted training and that the reaction is more of the motor type. This behavior was quite clear also in the Vogelsang /240 experiments. At the beginning, the two thoroughly studied test subjects showed reaction times fluctuating about two main values. With respect to the lower values, the statements made by the test subjects indicated that motor reactions were involved. With progressing training, obtained by hundreds of measurements, the longer values become increasingly less prominent. Finally, only short values were obtained, corresponding to the initial motor reaction times. It should be emphasized that the progressive training did not lead to shorter values than those obtained originally for the motor reactions. In addition, the start of training was characterized by the fact that the test subject no longer was able to obtain longer reaction times at sensory attitude. The reaction motion was innervated at the instant at which the sensation began. It might be that the start of training was somewhat accelerated in the Vogelsang experiments by the fact that both test subjects had considerable experience in measuring the sensation time. The accompanying table shows the sensation times (S.T.) and the reaction times (R.T.) measured on the test subjects Fr. and Vo.

	Fr.		Vo.	
Intensity	14 st. c.	0,5 NK	14 st. c.	0.5 st. c.
Reaction time, in σ	185	227	239	302
Sensation time, in σ	[illegible]	69	72	145
Motor component, in σ	152	158	167	157

A perusal of this table shows that, when using the weaker light stimulus of 0.5 standard candles (st.c.), both sensation time and reaction time become longer. It was also found that, in the test subject Vo., the reaction times were longer in accordance with his longer sensation times. This clearly indicates that, in both test subjects, the reaction time is only longer by the value of the longer sensation time and that, again in both test subjects, the motor component of the reaction time - despite the considerable differences in their sensation times - is within the same order of magnitude. To obtain further information on these conditions, Dr. Monjé was used as the third test subject; he

	14 st. c.		0.5 st. c.	
	Sensory R.T.	Motor R.T.	Sensory R.T.	Motor R.T.
Sensation time	35		75	
R.T.		189	293	240
Motor component	193	154	218	165

was well trained in measuring the sensation time but had very little experience in measuring the reaction time. The accompanying compilation gives the values obtained at sensory and motor attitude, using two different light intensities. /241

In the case of motor attitude, the reaction times for the test subject Mo. differed only by the magnitude of the measured sensation time, while the motor component was of the same order of magnitude as in the other two test subjects. Conversely, a comparison of the magnitude of the motor component at sensory attitude, as a function of the illumination intensity, showed that the motor component is larger even at an intensity which conditions the minimum sensation time and that it becomes still larger at weaker intensities. The latter result agrees fully with the findings by Hazelhoff and suggests that Hazelhoff's experiments had been made at sensory attitude of the test subjects.

The clearest result is furnished by experiments made at motor attitude of the test subjects. These furnish an important contribution to the personal equation, by indicating that, despite considerable differences in the sensation time, the motor component of the reaction time in the investigated test subjects always is within the same order of magnitude and remains the same even at different stimulus intensities. The reaction times differ only by the magnitude of the pertaining sensation time. This result obviously is a further substantiation for our experience with the sensation times, in so far as the differences in the measured sensation times coincide with the differences in the corresponding reaction times. Already in discussing the reaction time experiments, we mentioned that attempts had been made to draw conclusions as to the magnitude of the sensation time from the differences in the reaction times at differing intensity of stimulation. Here, we should mention primarily the studies by Cattell, Berger, and Piéron (Ref.102 - 104). At the same time, it is obvious that only a measurement of absolute values of the sensation time and an accurate allowance for the conditions prevailing in the reaction time experiments will make a determination of the segments of the reaction time possible.

In addition, more insight into the generation of sensory and motor reaction times is obtained. The longer duration of the sensory reaction time is readily explained by the fact that the attention is directed toward as rapid as possible an apperception of the sensory stimulus and thus is distracted from the motor reaction. The sensory reaction is predominantly observed in untrained test subjects. The beginner has more difficulty in performing the reaction at motor attitude, since the attention field is turned toward the sensory stimulus as well as toward performance of the reaction. As soon as distribution of attention has been learned, the magnitude of the sensation time becomes independent of the degree of attention; in addition, independently of the intensity of the sensory /242 stimulus or the magnitude of the personal sensation time, reaction is immediate as soon as the sensation is initiated. This will result in simple relations between S.T. and R.T., as they had originally been given in the paper by Vogelsang. All test subjects studied to date showed surprising agreement in the magnitude of the motor component of their reaction time; however, it is not inconceivable that studies, extended over a large number of test subjects, may reveal personal differences in the motor component of the reaction time. Certain literature data could be interpreted in this sense.

It is not difficult to understand that, in untrained test subjects or in the case of insufficient or unilaterally distributed attention - disregarding even the dependence of the magnitude of S.T. on various factors which had been discussed in detail earlier - the magnitude of the S.T. as well as of the motor component may vary as a function of the stimulus conditions, as had been specifically shown in the experiments by Hazelhoff and Vogelsang. This would correspond fully to experience of everyday life, except that it now has become possible to substantiate these experiences by actually measured time values. Similarly, it can be expected that, under conditions under which long sensation times occur, the reaction times also will be of longer duration. In fact, reaction time experiments, made with slowly moving light stimuli (Ref.105) as well as experiments with slowly amplifying vibration stimuli (Ref.106) or gustatory stimuli (Ref.107, 108) resulted in very long reaction times.

The experimental results by Vogelsang were challenged by Wirth (Ref.109) who believed it improbable that the motor component of the reaction time could remain unchanged at such widely differing motive intensities: he believed that the partial times of the reaction time would have to change under differing conditions of stimulation. This can be refuted by stating that, in the Vogelsang experiments, it was not a question of strength of motive but rather of intensity of stimulus. According to repeated statements by the test subjects, which also included the author of this paper, the reaction - in the case of motor attitude - takes place entirely independently of the intensity of light sensation, at the instant at which the light stimulus is perceived. Self-observation, under these conditions, thus strongly contradicts the hypotheses formulated by Wirth. This author also objected to the so-called subtraction principle (Ref.109, p.545) which was to yield information on the components of the reaction times, a principle applied repeatedly by Helmholtz, Donders, Exner, Wundt, and many others; this principle, according to Wirth, is merely of historical significance. However, it should be mentioned that the values of sensation time, obtained by Cattell, Berger, and Piéron (Ref.110 - 112) from the reaction times, on the basis of the subtraction principle at varying intensity of stimulation, agreed fully in order of magnitude with the differences of the absolute values of sensation time measured under similar conditions. It is impossible to simply disregard this coincidence. The objection by Wirth as to the changed influence of attention had been discussed earlier, at which time it was mentioned that Monjé (Ref.113) and Vogelsang emphasized specifically that the degree of attention, if attention is paid at all to the measurement, can have no influence on the results. In the experiments it is not a question of the recognition time but rather of the sensation time at which the sensory stimulus is not recognized or not evaluated, meaning that reaction takes place at the instant of occurrence of the sensation. The remark by Wirth that, according to Vogelsang, the test subject was not to pay attention to the point of stimulus application is due to a misunderstanding, since Vogelsang himself wrote as follows: "With respect to the sensation, the situation was different in so far as, in contrast to the sensation time measurements where the attention was centered on the point of the slit path at which the leading edge of the light strip would appear, only the apparition of the light strip was noted since this strip abruptly appeared with a certain width, with main emphasis being placed on rapidly performing the reaction after appearance of the strip. In this manner of observation, nothing was changed in the S.T. phenomenon but, as shown by special experiments, the reaction time was considerably prolonged by prior determination or apprehension of the spot at which the leading edge of the light strip was to appear." In this case, a recognition reaction would be involved, which naturally would have to be longer. /243

Similarly, with respect to the reaction time the question of the magnitude of the partial times of the motor component becomes of importance. The motor component contains the partial times accessible to the measurement, such as the conduction time within the nerves and the latency of the nerve-ending apparatus and the muscles. We are giving here the corresponding values despite the fact that they were taken from different studies and obtained under not fully comparable conditions. If, on the basis of investigations on the latent period of muscle and nerve-ending organs as well as of the conduction rate of human nerves, we make an allowance for the times in question for our reaction time experiments (Ref.114), a value of 20 σ will be rather too high than too low since about 135 σ would then remain for the processes in the continuous nerve cells. If we wish to further resolve this time, the studies by Bubnoff and Heidenhain /244

(Ref.115, 116) must be used, in which the latent periods were compared on stimulation of the cerebral cortex and, after decay of these times, on stimulation of the substantia alba. In these experiments, time differences of 45 σ occurred. In stimulation of the cerebral cortex, the latency was 80 σ while the corresponding value, in stimulation of the substantia alba, was 35 σ. This would indicate a considerable duration of the processes mediated by the cerebral cortex. In the remaining time of 135 σ, deducting the conduction time in the nerves from the motor component and the latency from the nerve-ending organ and the muscle, would have to include the transmission of the excitation from the sensory centers to the motor cortical centers as well as the latent period of the latter and of the motor centers of the spinal cord. This period, in view of the short reflex times of the spinal cord, cannot be excessively long, so that the high value of the motor component of the R.T. must be attributed mainly to the processes in the cerebral cortex. It should be recalled that, with respect to the sensation time, we had come to the conclusion that its duration is essentially conditioned by the processes in the sensory and nerve cells of the retina and in the visual center. This would also explain the long reaction times, which are measured on cut-in of higher consciousness processes.

Finally, we should briefly mention the reaction times in response to stimulation of different sensory regions. As a rule, the short reaction times of the auditory sense are mentioned; the reaction times mediated by the eye and the tactile sense are somewhat longer while the reaction times in the region of the gustatory and olfactory sense are longest. The mode of action of olfactory and gustatory stimuli would readily explain the long reaction times. However, if we wish to compare the reaction times, mediated by the various sensory regions, comparable conditions would have to be created. Wundt (Ref.61, p.405) already mentioned that, in presenting threshold stimuli, the differences in the reaction times mediated by the various sensory regions are eliminated; our own experience as to the maximal and minimal sensation times of various sensory regions fully confirmed the findings of Wundt. However, we mentioned previously that, in a /245 comparison of different sensory stimuli, not only the intensity but also the time course of the stimulus must be taken into consideration; in this respect, substantial differences occur already within one and the same sensory region, which become even more pronounced on comparison of different regions. For example, it is only necessary to compare the time course of a detonation or explosion with the time course of an olfactory stimulus. How is it possible at all to compare two such stimuli? One could possibly apply the principle used by Pulfrich (Ref.118) for heterochromic photometry, based on the equality of sensation time of two stimuli. This principle is realizable in nature, in numerous cases. At concentrated attention, it is possible to see an electric spark and hear it simultaneously during its jump; this means that a close correlation exists here between acoustic and optical stimulus, in intensity as well as in time course. It is quite justified to assume that stimuli of equal sensation time also involve equal reaction times. Consequently, the question as to the reaction times of different sensory regions can be solved only under consideration of the physiological effect of the sensory stimulus and the comparability of the stimulus course.

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